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CONTRIBUTION TO THE PETROGRAPHY OF THE KEWEENAWAN¹

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OUTLINE

INTRODUCTION

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INTRODUCTION

The effusive and clastic rocks of the southwestern extreme of the Keweenawan area, reaching into Minnesota, have been the subject of new study, more detailed than is reported in previous papers.² The main results are of two kinds, detail of outcrops, and a laboratory study of rock types and minerals, the latter of more general interest than the former. The new detail reveals no great error in the general maps recently published, but the map here presented shows the

¹ By permission of the Minnesota Geologic and Natural History Survey.

² R. D. Irving, "Copper-bearing Rocks of Lake Superior," *U.S.G.S. Mon. V*; Warren Upham and N. H. Winchell, *Minnesota Geol. and Nat. Hist. Survey*, II and IV (county reports); C. P. Berkey, "The Geology of the St. Croix Dalles," *American Geologist* (1897); C. W. Hall, "The Keweenawan Area of Eastern Minnesota," *Bull. Geol. Soc. Am.*, XII, 313.

region of new work, the exposures northeast of Kettle River being now mapped for the first time. The Keweenawan extends not over thirty miles west of the state line, and seventy miles north and south. Maps on a more accurate scale will be given in the reports of the survey when published.

Acknowledgments are due to Professor C. W. Hall for the conception of the work, and to Messrs. A. W. Johnston and W. Yeaton for field assistance.

GEOLOGY

SURFICIAL.—No detailed attention was given to the glacial features of the area, but in passing, it was seen that a great moraine occupied the southeastern side of Pine County, and that the tributaries of the St. Croix River cut through a great thickness of red sandy gravel. From this red drift, just south of the St. Croix, Dr. Berkey describes a laminated red clay, from the study of which he draws important conclusions as to the years that elapsed between two advances of glacial ice. No greater exposures were found than those described by Dr. Berkey, but the boundary including all such clays found in Minnesota indicates that the area is about four times as great as he explored (see Fig. 1).

RELATIONS.—To the south, Upper Cambrian sediments lie unconformably over the lavas of the Keweenawan. To the west and north, the lavas are in contact with more indurated sandstone, in a fault, the mapping of which has not been much altered by the discovery of new exposures. The correlation of the sandstone south on the St. Croix, with that northwest of the fault, is considered safe, but left uncertain by the fact that fossils are not known from the latter, by the unknown extent of the faulting movement, and even the direction of that movement. The dip of both sandstone and lava for several miles from the fault is southeasterly, as would be expected from an elevation of the sandstone, but observations close to the fault are few, and the rocks in these cases badly shattered. When the same contact is traced northeast into Wisconsin, clearer evidence points to a depression of the sandstone, and this is probably the best evidence of conditions in Minnesota.

STRUCTURE.—Within the Keweenawan some of the structure is equally uncertain on account of the scarcity of good exposures.

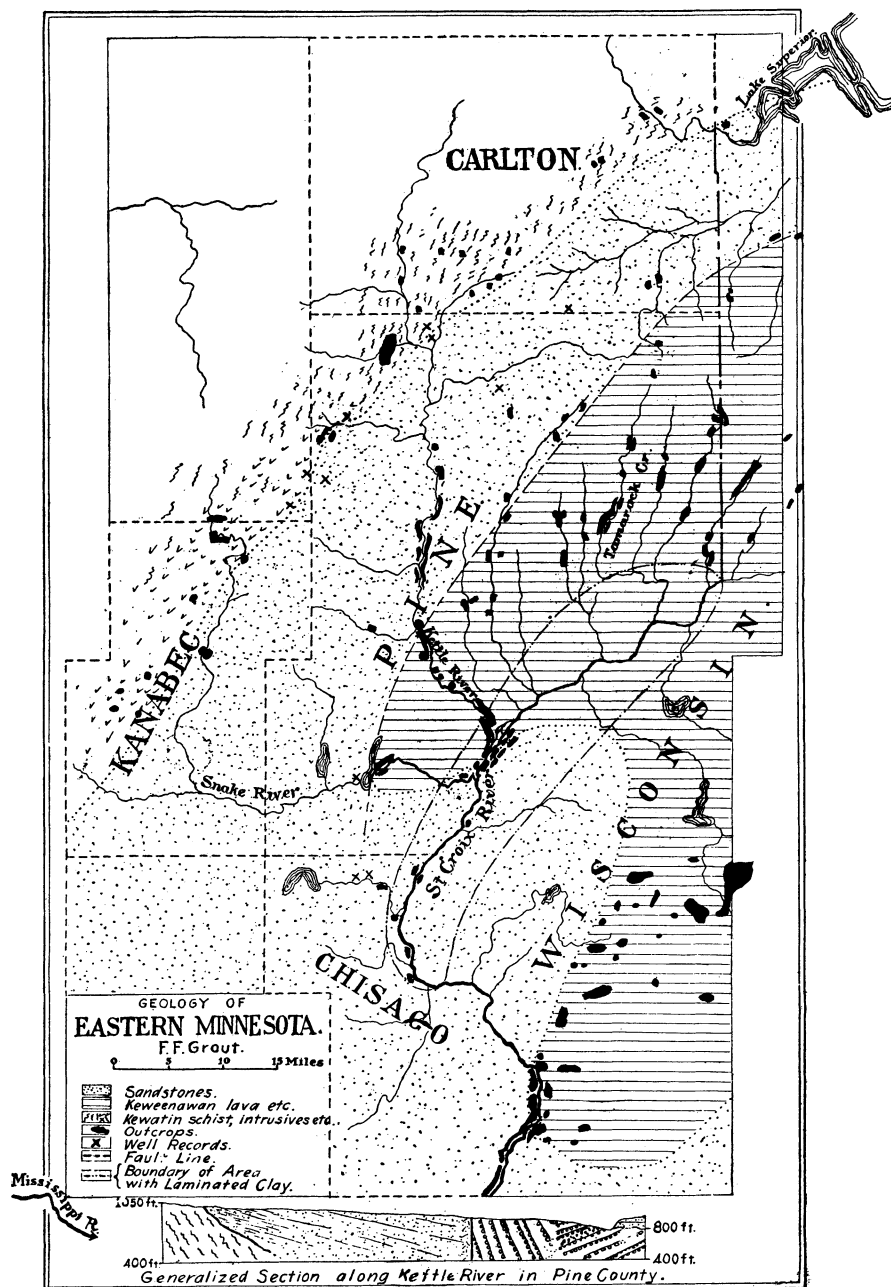


FIG. 1.—Map of eastern Minnesota and part of Wisconsin, showing outcrops and general geology.

Petrographically there is little that is new to the Keweenaw. The greater part of the rock originally occurred in surface flows, with an occasional conglomerate apparently formed along some shore-line. Beds of tuff, derived from volcanic ash and breccias, are not numerous, but are prominent in a few places. Intrusive dikes were not identified in this area. Evidence of the effusive nature of the rocks lies not so much in flowage structures as in the regular sequence of textures—a compact aphanitic basal portion grading into the



FIG. 2.—Ditch at Pine City, Minn., showing lava flows dipping 67° . Flows may be distinguished by the changes of the jointing in the amygdaloid.

coarser body of the flow, with often a characteristic amygdaloid breccia or ash bed before the next flow repeats the series. The jointing is in most places irregular, but in some columnar, as, for example, that producing the Devil's Chair at the Dalles of the St. Croix. The main jointing seldom persists into the amygdaloid, thus giving another means of distinguishing successive flows (see Fig. 2). The chief evidence of faulting is the development of slickensides in several places, and these may be along very minor fractures due to the extensive tilting of so thick a formation. There are no signs of the erratic discontinuance of a flow, or a shifting of position. Spheroidal weathering is quite common. Exceptional structures

develop locally; e.g., a banding simulating gneissic structure in a flow on Snake River, and a schistose streak a few inches wide in a flow seen by Berkey at Taylors Falls.

Near the fault the strike of the flows follows the fault quite closely. The general structure is a complex syncline. Beginning at the south, it is clear that the axis of the syncline must pass between the Taylors Falls rocks, dipping 15 degrees south, 70 degrees west, and the Snake River series, dipping 70 degrees south, 80 degrees east. On Kettle River the axis of the syncline is located within a few hundred paces. The flows farthest up the river, near the fault, dip 50 degrees south, 70 degrees east, and near the mouth other flows dip 20 degrees north, 70 degrees west. Near Kettle River the strike changes rather abruptly, swinging more easterly as one follows a flow northward. In this northeastern area no dip of more than 45 degrees was observed and no outcrop was found southeast of the synclinal axis. Some observations, however, indicate the proximity of the axis. In Wisconsin the axis was sketched by the early geologists,¹ running southwest close to the St. Croix, for a long distance, always on the Wisconsin side. To connect their observations with those on Kettle River requires a double curve in the axis, crossing the St. Croix near the mouth of Tamarack Creek. An alternative might be the suggestion that the sharp fold on Snake River, which becomes less sharp on Kettle River and still less on the next stream, gradually disappears to the northeast; and the whole may be a secondary fold in the northwest limb of the main Keweenawan syncline, which would then be nearly as Irving sketched it. No correlation of beds across the syncline has been possible. In the clear exposures of Kettle River series, several conglomerates are seen on the southeast and none on the northwest, but this may be an accidental disagreement in an incomplete series, because conglomerates are known on Snake River, west of the syncline.

AREAL.—The map (Fig. 1) shows the general region of outcrops. The three main types of lava distinguished in this paper are widely distributed and it cannot be said that any one of them is absent in any of the extensive series. Exposures are hardly clear enough to note any change in the general character from the earliest to the

¹ U.S.G.S. Mon. V.

latest flow exposed. About three strikingly peculiar types occurred in a few isolated outcrops and not elsewhere in the series. A line connecting the outcrops of a single type proves to run due northeast, conforming to the observed strike near by. Such data furnish the best evidence in Minnesota that a single flow is continuous for over 25 miles. The red laumontite pseudo-amygdaloid is so traced, and within two miles across the strike a highly porphyritic type runs parallel with it.

Geographically the area may be briefly summarized. The Taylors Falls and Snake River districts are discussed in earlier publications, but the remarkable freshness of one of the Snake River rocks is worthy of further mention. In the new area studied there are a few local variations. Most of the exposures are along creek banks. The rock types seen on the western side of the syncline on Kettle River are found due northeast on the smaller creeks. These types include the red pseudo-amygdaloid and a highly porphyritic rock on each creek. Along the lower parts of the eastern creeks the types vary somewhat, but seem to be local modifications rather than evidence of extensive changes of nature.

ECONOMIC.—Copper is found in small amounts in test pits on all the easily accessible streams. Its association varies—on Snake River where most explored, it is in laumontite, and on Kettle River, in prehnite. Some nice specimens are produced. In connection with the chemical side of this study of rocks, it was discovered that the fresh trap rock was the source of the copper. Indications are that the original lavas contained from 0.01 to 0.03 per cent of copper.

PETROGRAPHY

REVIEW.—Descriptions of Keweenawan rocks written between thirty and forty years ago have not been seriously questioned, though the method of naming rocks has developed greatly. All attempts, including this one, result in complex statements referring partly to original conditions, and partly to present altered ones. A summary and correlation of rock-names, in the literature, is given by A. N. Winchell,¹ so that the full list will be omitted.

Chemical data have been presented, in addition to field and micro-

¹ *Journal of Geology*, XVI, 765.

scopic results, by several authors, but only a few analyses are satisfactory for the application of chemical classification. These ancient basic rocks are so far altered in most places that the original can be only roughly estimated from the present composition. However, it seems clear that alteration results differently in different cases, and the average of several tests of a rock-type will give valuable indications of the quality of the magma. It is therefore worth while to

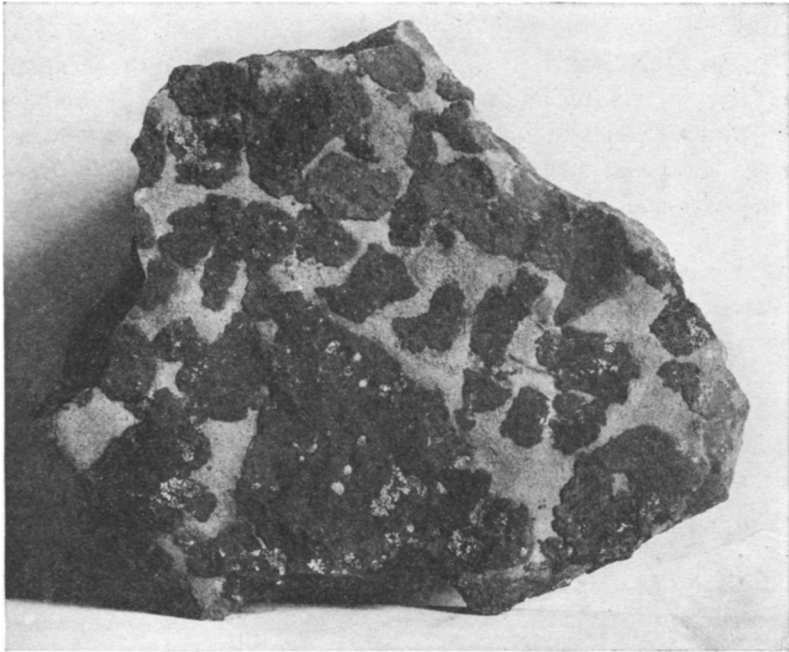


FIG. 3.—Weathered volcanic breccia. About one-half natural size

extend the chemical work, especially when material is very fresh, and analyses can be made quite complete.

CLASTIC ROCKS.—The conglomerates of this area have all been described in earlier papers and need no comment except that no correlation of beds has been possible, and that they give evidence that the boulders were derived from both Keweenawan and older formations.

Tuff and breccia, of the type found by Dr. Berkey at Taylors Falls, was found on the two tributaries of Tamarack Creek (Fig. 3).

The breccia consists of angular fragments of amygdaloid suspended in a fine-grained fragmental matrix identical with the tuff; and not, as suggested by Dr. Berkeley, suspended in the flowing lava or cemented by igneous material. The tuff is fine grained in most places, and the fragments angular; though rounded grains and water-sorting are not difficult to find. Alteration has produced a hard mass of quartz and epidote, an almost indestructible rock. Tuffs and breccias mark the boundary zone between two flows, though in a few cases fragments have been suspended in a later flow.

TYPES OF IGNEOUS ROCKS.—The rock-types described and pictured by earlier writers on the Keweenaw are not all represented in the lavas of eastern Minnesota. In fact, so few are represented that it is unnecessary to use as elaborate a table as A. N. Winchell presents in correlation of the early work. Of his types, based on modern petrographic usage, the area furnishes diabase and olivine diabase with some approaches to basalt and augite andesite, and the corresponding porphyries. In all the sections examined the essential of diabasic or ophitic texture was observed, viz., *the plagioclase needles formed before the augite*. This approaches a granular texture when augite is neither abundant nor coarse grained, but if the fundamental fact be kept in mind, all may be classed as modifications of diabase. No distinction is here drawn between augite and diallage; the presence or absence of olivine is of secondary importance like that of magnetite. The variation of the rock (or its alteration) is evidenced by the range in silica from 42 to 65 per cent. If reference is limited to this Minnesota area, the varieties are more clearly classified by varying texture than by the presence of olivine or other characters suggested by Mr. Winchell. The prevalent diabase is a quite uniform, compact rock with hackly fracture, coarse to fine grained (Fig. 4), grading, on one hand, by all degrees into a rock that is strongly luster-mottled (Fig. 5), also coarse to fine; and on the other hand, into a rock with clearly conchoidal fracture (Fig. 6), often red in color and usually fine grained. These field distinctions correspond to microscopic variations given below. They are to be correlated with Irving's "ordinary," "olivinitic," and "ash-bed" diabase, respectively, but are all included in Winchell's diabase and olivine diabase. All are easily accessible near Pine City, Minnesota.

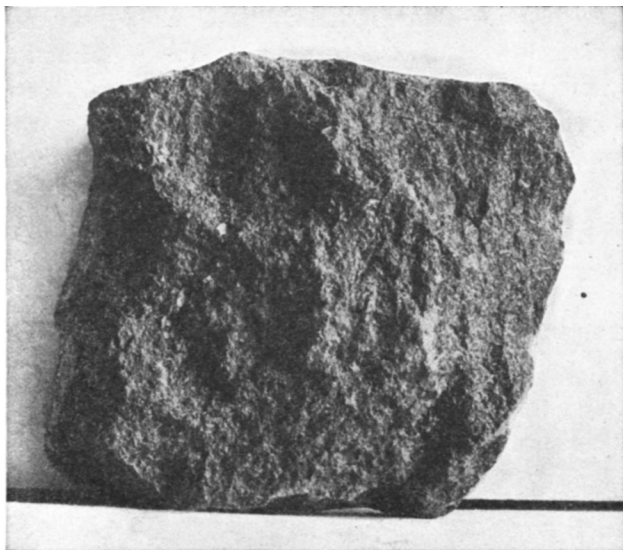


FIG. 4.—The common type of diabase showing hackly fracture. About one-half natural size.

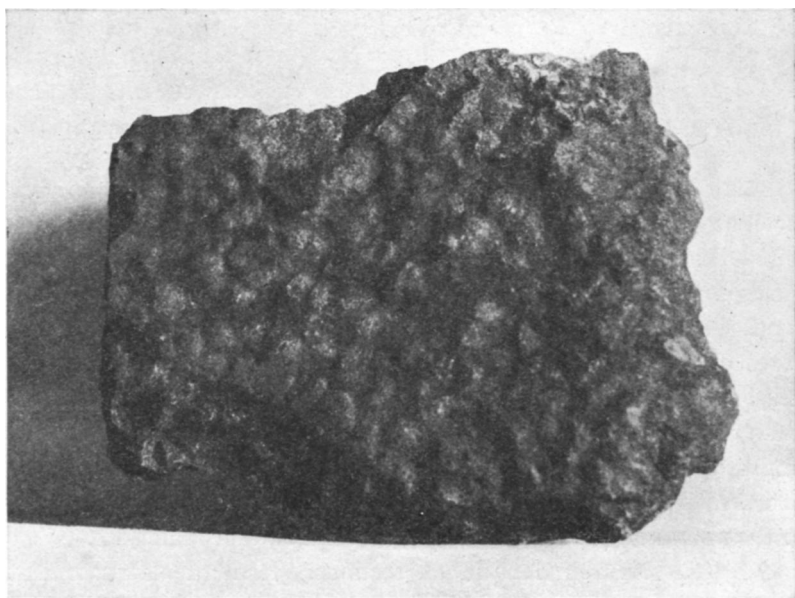


FIG. 5.—The weathered surface of luster-mottled diabase. About one-half natural size.

Mottled diabase.—This is probably the most easily recognized by the unskilled, from the fact that it invariably weathers to a color-mottling, and usually to pits or projections on the surface (Fig. 5). Colors depend upon the conditions of weathering. As a rule, the flows are thick, many of them weather spheroidally, and the amygdaloidal zone is not prominent. The latter point has made some occurrences seem more like intrusive than extrusive rock, but no such conclusion is forced upon one, here. Pumpelly's early description¹ has been widely accepted and its outline of the development of the rock is probably correct. He clearly presents the appearance of

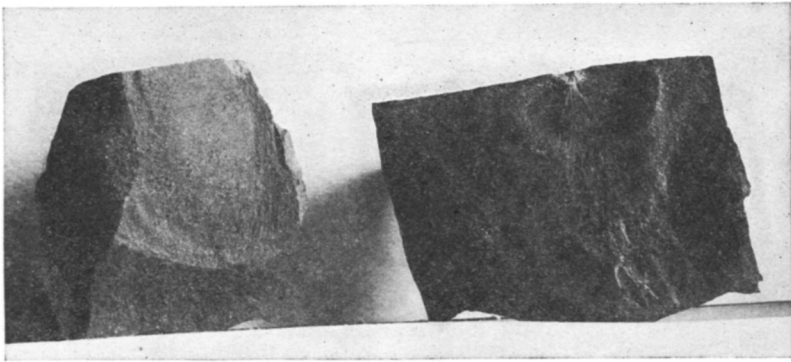


FIG. 6.—Conchoidally fracturing diabase. About one-half natural size

ophitic texture and the resultant luster-mottling. The original rock is reported as containing augite, plagioclase, olivine, and magnetite, with evidences of glassy matrix. Apatite is rarely seen. Alteration yields many other minerals. Of the fifty Minnesota rocks of this type, recently examined in detail, only one section revealed olivine cores of a size and freshness to yield an interference figure; but nearly all were well supplied with pseudomorphs, so similar to the fresh olivine as to be quite unquestionable, though the material was fibrous and pleochroic. Opaque minerals develop along the borders and cracks of the original grains, giving the impression of high relief to the alteration products, chlorite, serpentine, and iddingsite.

Magnetite is abundant in all sections. Hematite is prominent

¹ R. Pumpelly, *Geology of Wisconsin*, III, 33.

in some sections, chlorite in others, but the two seldom develop together.

The plagioclase is labradorite as determined by the maximum extinction angles, in sections perpendicular to the albite twinning. Zonal growth is not rare. The alteration of the feldspar is rather different from the average case described by Pumpelly. Prehnite is not a common product. Aside from a general dusty appearance, a granular light-green mineral develops in the central zone as if it were more easily altered than the outer zone. In extreme cases a complete pseudomorph results, faintly outlined in a ground-mass of no more definite character, and in the aggregate chlorite and orthoclase are indicated by analyses, if not optically. In a few cases secondary orthoclase crystals were identified. In a rather different alteration chlorite or some other green fibers grow up beside the feldspar as radiating groups, which encroach upon the lathlike grains, destroying their form and building a pseudo-amygdule.

Phenocrysts of plagioclase are neither common nor very large in the mottled rocks. When they appear, the composition is similar to that of the smaller crystals.

Augite is gray to brown, rarely showing the color due to titanium. It is one of the last minerals to be affected by alteration, which usually results in the borders becoming dark and dusty with chlorite. Rarely a pseudomorph occurs, light green, pleochroic, and with the extinction angles of hornblende.

In the coarser, fresher sections, the minerals that have been identified fill the space so completely that no room is left for glassy matrix, and none of the secondary products give the impression of resulting from such glass, or occupying its place. In the finer-grained parts of a flow—as near its base—a glass might be more probable, but even here are seen only the extreme alteration products and very little structure to indicate an original glassy condition. Another line of reasoning runs against the probability of much glassy matrix. Augite here appears to be one of the late crystallizations from the magma, and this mineral is commonly classed as a eutectic.¹ Hence it would begin to crystallize only after all those materials had separated, which made the fluid incapable of forming augite alone. It is hard to

¹ Cf. A. C. Lane, *Journal of Geology*, XII, 87-88.

understand how a matrix of the composition of augite should develop first some large crystals of that mineral, and later a glass of the same composition. The chlorite-like mineral which Pumpelly refers to glass, is admitted to be with difficulty distinguished from other chlorite in the rock.

TABLE I
ANALYSES OF MOTTLED DIABASES

1. Original type locality, Greenstone of Keweenaw Point, Mich. George Steiger, analyst. *Journal of Geology*, XVI, 765.
2. Taylors Falls, Minn., along railway track. F. F. Grout, analyst.
3. Tamarack Falls, Tamarack Creek, Pine Co., Minn. F. F. Grout, analyst.
4. Upper Tamarack Creek, Minn. Weathered red. A. W. Johnston, analyst.
5. Upper Tamarack Creek, Minn. Weathered green. A. W. Johnston, analyst.

	1	2	3	4	5
SiO ₂	47.69	48.88	47.82	48.07	46.99
Al ₂ O ₃	16.02	16.39	18.52	19.02	21.15
Fe ₂ O ₃	2.41	5.51	6.39	7.65	7.14
FeO.....	8.70	7.21	3.15	4.83	3.94
MgO.....	8.31	5.80+	8.20	3.30	2.73—
CaO.....	10.54	9.11	11.09	9.84	2.17
Na ₂ O.....	2.44	2.08	1.67	2.84	0.80
K ₂ O.....	none	0.47	0.17	0.63	6.12
H ₂ O—.....	0.44	0.19	0.66	0.43	1.30
H ₂ O+.....	2.04	2.15	1.53	1.69	6.32
TiO ₂	1.38	1.84	0.78	1.72	0.92
CO ₂	none	0.09	0.17	none	none
P ₂ O ₅	0.06	0.10	0.05	none	0.56
S.....	none	0.05	0.04	0.11	0.14
CuO.....	....	0.02	trace	....	....
MnO.....	0.26	0.15	0.12	0.21	0.12
BaO.....	none	0.02	0.02	0.02	none
SrO.....	none	none	none	0.02	0.03
Cr ₂ O ₃.....	....	none	0.03	0.18	0.06
	100.29	100.06	100.41	100.56	100.49
Specific gravity.....	....	2.974	2.898	....	....
	*Auvergnose	Hessose	Hessose	Hessose	....

* For the significance of these names see *Journal of Geology*, X, 555.

The alteration was Pumpelly's special study¹ and proved interesting and complex. For details of the several successive changes, reference must be had to the original. The chloritic minerals are of greatest interest, and their nature is variable in each of the several types of occurrence, as shown below.

¹ R. Pumpelly, *Proc. Am. Acad. Arts and Sciences*, XIII, 253.

The composition of the mottled type is indicated by the analyses of Table I, but each of the Minnesota samples is considerably altered. Nevertheless the calculated norm confirms the field conclusion that there was considerable variation in the proportion of minerals in the originals, and even some variety in the composition of some of the silicates.

Hackly diabase.—Microscopically these rocks are usually coarse grained but mineralogically similar to the mottled type. The texture is diabasic as distinct from ophitic, though intermediate textures are not rare. Many of the flows have well-defined amygdaloidal zones. Pumpelly's study of the metasomatic development of secondary minerals has been checked, as far as material was available, and Minnesota furnishes one type which he did not find well developed—the laumontite rocks.

Olivine was found in sections from one flow of hackly rock in Minnesota. Pseudomorphs, clearly from olivine, were found in about half the sections of this type; but some rocks, closely resembling these, showed no product or structure indicating that olivine had ever been present. The one Minnesota rock showing fresh olivine is so fresh compared with other flows of the region as to be hard to place with them, but there is no sign of mottling, and the texture is far from the typical ophitic. It gave Analysis 3, of Table II. The olivine is just beginning to alter along the borders and cracks to a chloritic mineral of strong pleochroism in brown and green. A little chlorite appears in other parts of the rock, but no room is left for any glass or its alteration products. This occurrence may well be substituted, in general discussions of the Keweenawan, for the type locality given in Michigan, No. 87 of Marvin's Eagle River section. However, it is not suggested that all hackly diabases were olivinitic. Olivine is present in this freshest sample, and its presence or absence is not a good point to use as a type characteristic. The pseudomorphs after olivine vary as before, and the development of magnetite and hematite along the cracks gives the pseudomorph the appearance of the high relief of olivine, in fully half the sections examined. Some of the pseudomorphs give a uniaxial figure, as recorded by Pumpelly.

In the fresh flow of the Snake River series, labradorite is the feldspar, but in the more altered samples very few crystals are fresh

enough to show twinning bands. In these the extinction is wavy and angles are low. Both oligoclase and orthoclase are probable.

Magnetite is seen in all sections and apatite in only one.

Alteration in most cases has proceeded even farther than in the mottled rocks, and resulted in a pseudo-amygdaloid—a botchy mass of secondary minerals. The original texture is revealed by some pseudomorphs, one of the most peculiar being a nearly opaque yellowish-green earth with the form of plagioclase. However, the pseudo-amygdules are quite abundant, developing from any spot as a nucleus, and expanding as they replace the surroundings with a new layer. Chlorite is the commonest material, varying from colorless to dark blue-green, or yellow, or brown, or gray, and usually spherulitic. In similar position in other rocks are calcite, quartz, epidote, actinolite, and a dusty red mineral of very feeble birefringence, which may be laumontite or some other zeolite. Regarding the development of most of these, reference must be had to Pumpelly's paper, but some new work is here offered regarding the laumontite rocks. There is an extensive development of this mineral in some amygdaloidal and vein cavities on Snake River in Minnesota. Its properties are given below with those of other amygdules. Beginning at Kettle River and extending twenty-five miles northeast, is a series of outcrops of a red pseudo-amygdaloid, associated with which are real amygdaloids with red laumontite. The red material of the pseudo-amygdules appears to be similar to that of the amygdules, but the rocks are badly softened and microscopic examination is not very satisfactory. A specific gravity separation of the rock-constituents yielded rather mixed material, the lightest fraction being strongest red in color. Chemical tests of the two lightest fractions show that there is an approach to laumontite (Analyses 4 and 5, Table VI), and there is no doubt that this mineral has developed in the rock-matrix as well as in the cavities. Pumpelly suggests the possibility, and thinks it an early product in the alteration. Its associates here are badly altered; only augite, of the original, is still recognizable in the mass, which affords clear evidence of its original texture.

An entirely distinct line of chemical work has given a hint of the history of some of the rocks. This is the composition of the product

of alteration of laumontite. Where excellent crystals of laumontite are found on Snake River, some perfect pseudomorphs were found with an entire change in certain constituents. Lime is lacking in the secondary mineral and potassium is prominent. In several parts of the area amygdules were found of similar character to this pseudomorph, and an analysis shows the chemical constituents to be similar. This development of a potassium mineral may not be a conclusive proof of the former presence of laumontite, but adds probability to the idea. In other places and other rocks, the potassium minerals found have very different characters. Further, on Upper Tamarack Creek this same mineral is largely developed with chlorite in a pseudo-amygdaloid, which may be a late derivative of the laumontite pseudo-amygdaloid. Analyses of these minerals are given in Table VI, but of the rocks in Table II.

TABLE II

ANALYSES OF HACKLY FRACTURING DIABASES

1. Taylors Falls, Minn. Rather fine grained. C. A. Taylor, student analyst.
2. Crooked Creek, Pine Co., Minn. C. Tronson, student analyst.
3. Pine City, Minn. Coarse and fresh. F. F. Grout, analyst.
4. } { Altered hackly diabase, forming a belt of laumontite pseudo-amygda-
5. } { loidal outcrops, across the area of Keweenawan in Minnesota. F. F.
6. } { Grout, analyst.

	1	2	3	4	5	6
SiO ₂	48.68	53.20	48.27	42.35	47.22	47.54
Al ₂ O ₃	19.29	15.83	16.29	17.24	17.17	17.40
Fe ₂ O ₃	4.07	3.39	4.55	9.90	10.21	9.21
FeO.....	8.31	6.79	10.09	2.69	2.47	2.71
MgO.....	5.52	5.44	4.94	7.01	5.00	5.14
CaO.....	7.78	6.95	8.42	7.47	6.58	6.40
Na ₂ O.....	3.49	3.73	2.14	0.93	2.70	2.61
K ₂ O.....	1.16	1.34	0.77	1.48	2.15	1.80
H ₂ O—.....	0.10	0.63	0.64	1.57	0.54	0.73
H ₂ O+.....	0.16	1.44	1.67	7.13	3.73	4.38
TiO ₂	1.70	1.35	2.46	1.84	1.96	1.79
CO ₂.....	.....	.....	0.05	0.10	none	0.15
P ₂ O ₅	0.05	.....	0.14	0.14	0.15	0.06
S.....	.....	.....	0.04	none	none	0.04
MnO.....	.....	0.15	0.17	0.15	0.12	0.11
BaO.....	.....	.....	0.04	0.01	0.03	0.02
Cr ₂ O ₃.....	.....	.....	none	0.01	0.02	0.02
	100.31	100.24	100.71*	100.02	100.05	100.11
Specific gravity....	.....	.....	2.986	2.695	2.821	2.778
	Hessose	Andose	Auvergnose	.....	.....	.....

* CuO=0.03.

Conchoidally fracturing diabase.—This fracture appears only in the base of most flows, but throughout the whole mass in a few flows. The augite in these is less prominent and in small grains. The feldspar, also fine, is labradorite, oligoclase, or even orthoclase when recognizable. Olivine has not been recorded, but A. C. Lane concludes from the form of some secondary minerals, that they replace olivine. The composition indicates that olivine might develop, but, as in the previous types, it is best to assume its presence in some, but not all, of the rocks of this field type.

TABLE III
ANALYSES OF CONCHOIDALLY FRACTURING DIABASES

1. Type locality, Bed 65, Eagle River section, Keweenaw Point, Mich. George Steiger, analyst. *Journal of Geology*, XVI, 765.
2. Crooked Creek, Pine Co., Minn. Average material. F. F. Grout, analyst.
3. Tamarack Creek, Pine Co., Minn. Altered, but hard. F. F. Grout, analyst
4. Mouth of Kettle River. Altered to red clay. Partial analysis by F. F. Grout.

	1	2	3	4
SiO ₂	50.07	53.16	63.00	43.35
Al ₂ O ₃	12.63	15.12	14.01	20.42
Fe ₂ O ₃	3.84	5.95	6.42	} 13.57
FeO.....	10.30	6.75	0.44	
MgO.....	5.23	4.76	2.83	5.17
CaO.....	6.55	5.74	0.85	0.27
Na ₂ O.....	3.53	2.38	1.82	0.35
K ₂ O.....	1.90	1.54	5.42	5.46
H ₂ O—.....	0.86	0.38	0.26	4.24
H ₂ O+.....	1.96	1.92	1.93	5.54
TiO ₂	2.50	1.68	0.63	0.92
CO ₂	none	0.05	0.07	....
P ₂ O ₅	0.22	0.09	0.07	....
S.....	none	0.04	none	....
MnO.....	0.42	0.17	0.10	....
BaO.....	0.02	0.02	0.06	....
	100.03	99.75*	99.97	99.29
Specific gravity	.....	2.882	2.630	....
	Camptonose	Bandoë	Nameless Hispanare	....

* CuO=0.02.

Alteration giving hematite is probably responsible for the red color of many outcrops. Sections reveal the fine-grained pseudomorphs after plagioclase, in a ground-mass, usually darkened by hematite, especially where it seems probable an augite area existed.

A large part of the ground-mass is now orthoclase in one or two sections examined, but many other minerals are associated: quartz, calcite, chlorite, etc.

Porphyritic variations.—In Minnesota, phenocrysts from one-half to two inches long are developed in the conchoidal and hackly fracturing types at several localities. At Taylors Falls they are red and elsewhere usually gray. The fresh samples are labradorite, but alteration had the same effects on these large crystals that were revealed in the smaller ones. As the grain becomes dusty and granular, extinction becomes wavy, twinning bands disappear, and if there is an aggregate extinction the angle is low. A hard rock of this type can be followed along the strike for some miles on Kettle River. Two samples from widely separated points differ from each other so little that only the average is given in Table IV. The extreme was a variation from 6.05 to 6.89 per cent of lime. The phenocrysts have not affected the composition to make it differ much from non-porphyritic types.

Glasses.—A few inches at the base of each flow is commonly of the appearance of devitrified glass, and the immediate region of the amygdules at the tops of flows is similar. The alteration is advanced, though the crystallization is never very coarse. The conchoidal fracture remains, and in plain light the sections reveal microlites in a translucent field, and a few show flow structures.

Amygdaloidal textures.—Most of the flows have an upper zone, not sharply distinct from the main body, but characterized by increasing numbers of cavities, around which the rock is more glassy than elsewhere. Such porous glass, chemically unstable and physically weak, and affording good channels for water-circulation, now contains such a variety of secondary minerals that it seems hard at first sight to assign them all to the same rock for origin. Some cavities are now open—probably from recent leaching; some are filled with a single mineral; some contain three or four minerals in complex relation to each other. The series of minerals in order of formation has been generalized in the Michigan reports, and is essentially correct in this area. Table IV includes two analyses of Minnesota amygdaloids, but they are not in this particular Keweenawan area.

TABLE IV
ANALYSES OF AMYGDALOIDAL AND PORPHYRITIC ROCKS

1. Porphyritic diabase, Kettle River, east of Hinckley, Minn. Average of two samples, some miles distant. F. F. Grout, analyst.

2. Thomsonite-bearing rock, Good Harbor Bay, Lake Superior. C. F. Sidener, analyst.

3. Similar rock, decomposed, nearer Grand Marais, Lake Superior. C. F. Sidener, analyst.

	1	2	3
SiO ₂	50.48	46.80	45.37
Al ₂ O ₃	16.33	15.21	18.21
Fe ₂ O ₃	5.99	} 13.13	1.22
FeO.....	7.10		
MgO.....	4.08	8.13	6.98
CaO.....	6.47	11.11	11.49
Na ₂ O.....	2.44	1.95	0.84
K ₂ O.....	1.39	0.01	0.02
H ₂ O—.....	0.46	....	....
H ₂ O+.....	2.70	2.79	4.66
TiO ₂	2.15	....	....
CO ₂	0.01	....	....
P ₂ O ₅	0.21	....	....
S.....	0.01	....	....
CuO.....	0.02	....	....
MnO.....	0.16	....	....
BaO.....	0.04	....	....
	100.04	99.13	99.77
Specific gravity ...	2.886	.....	.....
	Bandose	Auvergnose	.....

Amygdules and other secondary rock minerals.—Chlorite is probably the most important mineral of this group, forming amygdules, pseudo-amygdules, and pseudomorphs after glass, olivine, augite, and even plagioclase, with prehnite as an intermediate product. The similarity of constituents of this green earth and augite suggests that much of it originated from that mineral, and this idea is confirmed by the absence of much chlorite in the rocks low in augite. The variety of occurrence, however, as well as some small variations in optical properties, indicates several methods of formation and a variable composition. An early test of composition, by McFarlane of the Canadian Geological Survey,¹ by fractional solution in nitric acid and alkali gave a solution indicating the composition of delessite.

¹ Canadian Geol. Survey, *Report of Progress*, 1863–66.

Pumpelly had an analysis made with similar results. Both samples represented pseudo-amygdules, and the results have been widely accepted, though it seems possible some other constituent may have been attacked with McFarlane's chlorite. Dr. Berkey¹ found the chlorite amygdules of Grand Marais on the north shore of Lake Superior to be strigovite. Three of the samples now tested seem to be much like delessite and the fourth does not seem to be a definite chlorite. The analyses, though similar to those given by Dana, are quite different from earlier analyses of Keweenawan material. Those

TABLE V
ANALYSES OF CHLORITE AND "GREEN EARTH"

1. Chlorite, silky amygdules, Pine City, Minn. F. F. Grout, analyst.
2. Chlorite pseudo-amygdules, Upper Tamarack Creek, Minn. F. F. Grout, analyst.
3. Green earth of slickensides, Crooked Creek, Minn. F. F. Grout, analyst.
4. Green mineral from rock analyzed, Number 3, Table IV. C. F. Sidener, analyst.

	1	2	3	4
SiO ₂	31.84	31.87	44.60	39.00
Al ₂ O ₃	18.32	17.58	6.93	8.41
Fe ₂ O ₃	2.59	7.63	9.59	} 10.69
FeO.....	13.80	8.67	3.94	
MgO.....	20.64	20.81	19.98	19.64
CaO.....	none	trace	0.74	3.59
Na ₂ O.....	trace	none	0.61	0.29
K ₂ O.....	trace	0.92	0.15	none
H ₂ O—.....	1.80	0.47	8.00*	....
H ₂ O+.....	10.40	11.63	5.00	17.07
CO ₂	0.13	....	0.13	....
TiO ₂.....	....	0.15	0.06	....
	99.52	99.73	99.73	98.69
Specific gravity	2.739	2.777	2.500	.....

* The moisture lost on drying at 100°, though great, was almost entirely regained after exposure to ordinary air.

were low in magnesia and high in alumina and iron oxides. The high ferric oxide which has been mentioned in connection with reduction of copper is less prominent in these new analyses. The chlorite has a hardness of about 2, and the color varies—usually green and light enough so that sections are very faintly colored. The structure

¹ C. P. Berkey, Minn. Geol. and Nat. Hist. Survey, *Ann. Report* 23, 194.

is usually radial, but in some, confused and very fine grained; double refraction is very slight and still notably variable.

Probably second in importance as an alteration product in these rocks are laumontite and related minerals. Their occurrence is mentioned above and it is now time to discuss the evidence of the relation of laumontite to an aggregate of quite different composition. The laumontite crystals, occurring on Snake River in greatest abundance, are red in color and usually form radiating groups up to two inches across. Terminal faces have developed on distinct prisms up to a quarter of an inch in thickness. The termination is the common laumontite form, classed as a dome (201) by Dana. The angle from prism to this dome varied quite widely in the crystals measured, but apparently this was due to the enlarging prism in the radiating group. Several measurements, by both hand and reflection goniometers, lay very close to the correct figure $113^{\circ} 30'$ and the rest varied within 5 degrees below that value, with no point more prominent than the rest. A trace of the pinacoid face could be seen on a few crystals. The prismatic cleavage is prominent, especially after the mineral has stood a time in a dry warm room. The blowpipe and physical characters clearly identified it.

Thin sections indicate hematite as coloring matter rendering the section dusty, but other alteration products contributed to this effect. Extinction was often wavy, and inclusions of different orientation crossed some grains in such a way as to remind one of micropertthite. Such was the material of Sample 2, Table VI.

Light-green pseudomorphs formed from this red mineral. They preserved the angles of the original and showed the same development and imperfections. In a few illustrative specimens, the red center of laumontite is visible in broken green prisms. The cleavage cracks of laumontite show as light or more transparent lines in the pseudomorph. At this type locality, the chief chemical change is the replacement of lime and some water, by potash and magnesia. No formula is yet suggested for the mineral, however, because of the variation in similar material from other localities. It has a hardness of 3; specific gravity of 2.7; fusibility of 3; soapy feel; is an aggregate of grains, none of which was over 0.01 mm. in length; is anisotropic and has medium birefringence. Hydrochloric acid dissolves very little, and

TABLE VI

ANALYSES OF LAUMONTITE AND RELATED PRODUCTS

1. Light-pink laumontite, Pine City, Minn. F. F. Grout, analyst.
2. Dark-red laumontite, Pine City, Minn. F. F. Grout, analyst.
3. Dark-red laumontite, Kettle River, Minn. F. F. Grout, analyst.
4. Lightest fraction of red pseudo-amygdaloid, Crooked Creek, Minn. This is not a clean separation from feldspar, as shown by the next sample. F. F. Grout, analyst.
5. Next to the lightest fraction of the foregoing sample, No. 4. F. F. Grout, analyst.
6. Green pseudomorph after laumontite like sample No. 2. F. F. Grout, analyst.
7. Appeared to be bleached and further altered from sample No. 6. F. F. Grout, analyst.
8. Amygdules of similar appearance, Upper Tamarack Creek, Minn. F. F. Grout, analyst.
9. Pseudo-amygdules of similar appearance, associated with chlorite and hematite, Upper Tamarack Creek, Minn. F. F. Grout, analyst.

	1	2	3	4	5	6	7	8	9
SiO ₂	51.34	49.66	49.44	48.85	53.58	53.73	53.02	62.78	48.80
Al ₂ O ₃	22.48	21.15	20.62	25.01	} 26.16	15.08	20.55	15.52	19.63
Fe ₂ O ₃	0.55	1.32	2.86	2.19		4.24	1.94	2.06	} 8.87
FeO.....	0.15	0.21	trace	trace		2.36	1.36	0.20	
MgO.....	0.97	1.44	1.29	1.73	1.67	9.12	7.31	3.19	7.50
CaO.....	10.68	9.16	9.46	6.84	5.56	0.08	0.08	none	trace
Na ₂ O.....	1.23	1.49	0.60	2.36	3.90	0.38	0.72	none	0.30
K ₂ O.....	0.40	1.38	1.66	2.21	3.16	8.02	6.20	5.82	5.98
H ₂ O—.....	1.66	2.90	2.40	2.00	....	1.02	1.82	6.23	1.74
H ₂ O+.....	10.14	10.80	11.97	9.34	....	5.55	5.36	4.50	6.30
CO ₂	0.10	0.12	....	....	....	....	....	....	....
TiO ₂.....	....	....	0.18	0.10	....	0.03	trace	0.06	0.77
	99.70	99.63	100.48	100.63	Incom- plete	99.61	98.36*	100.36	99.89
				less than					
Specific gravity	2.353	2.315	2.381	2.580	2.581	2.750	2.677	2.581	....

* Two sets of duplicate analyses yielded consistently low summation. The alkali determination showed the poorest agreement; and the figure reported is that from the two highest results which were in close agreement. Sulphur, and carbonic acid are not present in amounts sufficient to change the total much.

yields no jelly as laumontite does. By thorough treatment with this acid and alkali, only 25 per cent is extracted and the extract resembles the original except in having more iron and none of the sodium and potassium. However, the addition of sulphuric acid, in the above treatment, makes decomposition complete. As the orthoclase of this same district gives only 3 per cent to this treatment, it seems certain

that this material is not a mixture of orthoclase and another mineral. No other mixture seems to fit the case and although the analyses show considerable variation it is quite certain that we are dealing with material not hitherto described. At least, it is a new alteration product for laumontite. It is here proposed that the new mineral be called *pseudo-laumontite*. Chemically it is unique in combining potassium and magnesium in a silicate. The rock-analysis No. 5, of Table I, resembles the analyses of pseudo-laumontite closely enough to be of interest in this connection.

TABLE VII
ANALYSES OF MISCELLANEOUS AMYGDULES

1. Orthoclase, fine-grained, salmon-pink tufts lining cavities, T.39N., R.21W., Pine City, Minn. F. F. Grout, analyst.
2. Analcite, red and white mottled crystals, associated with either laumontite or orthoclase, Pine City, Minn. F. F. Grout, analyst.
3. Prehnite, radiating groups in a light-green vein-filling, T.41N., R.20W., Kettle River, near Hinckley, Minn. F. F. Grout, analyst.
4. Datolite, enamel-like bunches, associated with chlorite in cavities, Pine City Minn. F. F. Grout, analyst.
5. Chalcedony, Crooked Creek, Pine Co., Minn. F. F. Grout, analyst.

	1	2	3	4	5
SiO ₂	61.69	55.76	45.31	36.50	97.85*
Al ₂ O ₃	19.46	23.24	20.60	trace	0.18
Fe ₂ O ₃	0.76	0.53	5.45	3.58	} 0.46
FeO.....	0.93	0.40	trace	trace	
MgO.....	0.52	0.55	0.63	1.25	0.17
CaO.....	trace	trace	23.66	33.28	0.30
Na ₂ O.....	0.20	11.79	0.31	none	p.n.d.
K ₂ O.....	15.00	0.07	0.19	0.10	p.n.d.
H ₂ O—.....	0.10	0.10	0.16	0.16	none
H ₂ O+.....	0.97	8.06	4.40	5.95	1.00
CO ₂	0.15	0.15	....	0.20	none
TiO ₂	0.10	trace	....	0.10	0.04
B ₂ O ₃.....	....	....	....	18.88*	....
	99.88	100.65	100.71	100.00*	100.00*
Specific gravity.....	2.615	2.283	2.896	2.951	2.618

* The percentage of silica in chalcedony and of boric acid in datolite are found "by difference." The difficult method of estimating boric acid gave the analyst 17.36 per cent B₂O₃ instead of 18.88. Material was exhausted before it was satisfactorily checked.

Several other minerals have been tested, chiefly by analysis, to estimate their purity. Analcite yielded measurable crystals of the common form. All of the mineral occurrences recorded with the

analyses are new occurrences. As datolite is new to the state except in the drift, it is worthy of record that it has another occurrence, on Crooked Creek. Record of metallic copper from many points might be made, but the mineral needs no analysis, except for silver, which was not found.

THE CHEMICAL CLASSIFICATION.¹—Grouping the twelve new analyses of rocks that show little alteration (less than 3 per cent combined water) with five earlier results which seem to be good, the chemical character of the diabases may be summarized. More results fall in the subrang *Hessose*, than any other, and this is a persodic, docalcic, perfelic dosalane. The similar groups Bandose

TABLE VIII

ANALYSES OF BASIC DIABASE DIKES OF MINNESOTA

1. Diabase dike, Stearns Co., Minn. B. F. Noehl, student analyst.
2. Olivine diabase dike, Carlton Co., Minn. W. H. Truesdell, student analyst.
3. Diabase dike, Stearns Co., Minn. Average of two analyses, side and center of 14-foot dike, essentially the same. F. F. Grout, analyst.
4. Diabase with phenocrysts of quartz and feldspar in a 5-foot dike. F. F. Grout, analyst.

	1	2	3	4
SiO ₂	50.51	49.34	48.45	52.01
Al ₂ O ₃	15.30	13.03	12.70	17.56
Fe ₂ O ₃	1.79	2.50	2.00	0.00
FeO.....	8.14	13.74	13.24	8.61
MgO.....	5.94	3.64	4.39	4.90
CaO.....	9.04	7.40	8.50	7.55
Na ₂ O.....	5.18	4.55	3.94	3.72
K ₂ O.....	2.00	1.57	1.22	1.70
H ₂ O—.....	0.00	0.24	0.00	0.00
H ₂ O+.....	1.43	0.69	1.58	1.57
CO ₂.....	....	0.96—	0.00	....
TiO ₂	2.80	3.16	3.17	0.92
ZrO ₂.....	....	0.04	....	....
P ₂ O ₅.....	....	0.15	0.72	0.20
MnO.....	0.51	0.51	0.17	0.11
S.....	....	0.12	....	....
BaO.....	....	0.03	....	....
Cr ₂ O ₃.....	....	0.02	0.10	0.20
	102.64	101.64	100.18	99.95
Specific gravity	....	....	2.90	2.840
	Limburgose	Kilauose	Auvergnose	Hessose

¹ *Journal of Geology*, X, 555.

and Auvergnose are well represented. Of the 17 analyses, 17 are persodic, 12 are docalcic, 12 are perfelic, 10 are dosalic. The variation of the others is not uniform.

Such relationships in composition may be taken as evidence of origin from a common magma, and the differences that exist in the unaltered rocks are therefore to be attributed to some process of differentiation. Alteration is too great for accurate discussion of the subject. Mr. Lane has raised the question of differentiation in a single flow.¹ His opportunity to examine extensive drill cores, gave him results that are beyond comparison with any now to be added from a rapid field survey. He found some changes which appeared to be due to an early separation of oligoclase which was lighter than the basic magma, and rose, affecting both composition and texture. Analyses are offered in confirmation, but the high degree of alteration, indicated by 5 per cent water and 1 per cent carbonic acid, makes the chemical evidence of much less value than the microscopic work. Mr. Lane does not suggest that such action was common in the

TABLE IX
ANALYSES OF BASIC LACCOLITHS OF MINNESOTA

1. Gabbro, Richmond, Minn. E. M. Pennock, analyst.
2. Gabbro, Little Falls, Minn. Miss Lillian Nye, student analyst.
3. Gabbro, Duluth, Minn. Several student analysts obtained results, from 102 to 103 per cent. The lowest is by G. H. Stone, given below.

	1	2	3
SiO ₂	52.34	44.16	49.42
Al ₂ O ₃	14.17	14.89	24.47
Fe ₂ O ₃	2.40	1.19	3.13
FeO.....	10.78	6.83	6.13
MgO.....	3.51	14.40	1.00
CaO.....	7.25—	13.01	8.45
Na ₂ O.....	3.73	1.92	4.98
K ₂ O.....	2.37	0.97	1.15
H ₂ O—.....	0.18	0.05	0.06
H ₂ O+.....	0.43	0.89	0.55
TiO ₂	2.21	0.89	1.87
P ₂ O ₅	0.80—	....	0.04
MnO.....	0.09	trace	0.11
S.....	0.14+	....	0.11
	100.40	99.30	101.48
	Camptonose	Portugare	Andose

¹ A. C. Lane, *Michigan Geol. Survey*, VI, 215.

Keweenawan, and no such case has been noted in Minnesota. Slight peculiarities were not rare; as, for example, the gneissic appearance, mentioned by Professor Hall regarding a Pine City exposure. This was prominent in the lower twenty-five feet of a thick hackly flow.¹

In Michigan some diabase dikes in rocks near the lavas have been compared with the lavas, as an indication of their relationship. A similar comparison may be instituted here for Minnesota, and extended to include other occurrences of basic rocks in the central and northeastern part of the state. Earlier analyses reported by Streng, Winchell, and Irving are included in the tabular comparison, but analyses are not quoted.

TABLE X
CHEMICAL CLASSIFICATION BY LOCALITY AND FORM

	Labradorose	Dacose	Varingase	Tonalose	Bandose	Shoshonose	Andose	Hessose	Vaalose	Kilauose	Camptonose	Ornose	Auvergnose	Limburgose	Dosodic Docalcic Portugare
Minnesota flows.....	-	-	+	+	+	-	+	+	-	-	+	-	+	-	-
Michigan flows.....	-	-	-	+	+	-	+	+	-	-	+	+	+	-	-
Minnesota dikes.....	-	-	-	-	-	+	-	+	+	+	-	-	+	+	-
Michigan dikes.....	-	-	-	-	-	-	-	+	+	+	-	-	+	+	-
Duluth gabbro.....	+	+	-	-	-	-	+	+	-	-	+	-	+	-	-
Stearns Co. gabbro....	-	+	-	-	-	-	+	+	-	-	+	-	+	-	±

TABLE XI
TYPES OF DIABASE CHEMICALLY CLASSIFIED

	Hispanare	Tonalose	Bandose	Shoshonose	Andose	Hessose	Kilauose	Camptonose	Auvergnose
Mottled type	-	-	-	-	-	+	-	-	-
Hackly type.....	-	+	+	-	+	+	-	+	+
Conchoidal type ..	+	-	+	-	-	-	-	-	-
Dike rock.....	-	-	-	+	-	+	+	-	+

¹ C. W. Hall, *Bull. Geol. Soc. Am.*, XII, 313.